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Attributing the increase in atmospheric CO_2 to emitters and absorbers

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Climate change policies need to consider the contribution of each emitting region to the increase in atmospheric carbon dioxide. We calculate regional attributions of increased atmospheric CO_2 using two different assumptions about land sinks. In the first approach, each absorber region is attributed 'domestic sinks' that occur within its boundaries. In the second, alternative approach, each emitter region is attributed 'foreign sinks' that it created indirectly through its contribution to increasing CO_2. We unambiguously attribute the largest share of the historical increase in CO_2 between pre-industrial times and the present-day period to developed countries. However, the excess CO_2 in the atmosphere since pre-industrial times attributed to developing countries is greater than their share of cumulative CO_2 emissions. This is because a greater fraction of their emissions occurred more recently. If emissions remain high over the coming decades, the share of excess CO_2 attributable to developing countries will grow, and the sink service provided by forested regions—in particular those with tropical forest—to other regions will depend critically on future tropical land-use change.

Decreasing the risk of dangerous climate change requires a decline in future emissions of CO_2 to the atmosphere. There are three controls on the increase of atmospheric CO_2 (ref. 1): fossil fuel and cement emissions; land-use change emissions mainly from deforestation (∼11% of all emissions from human activity[1]); and land and ocean sinks. Climate policies mostly aim at reducing fossil fuel emissions because they constitute the largest flux driving the global increase of CO_2 and much of the emissions come from point sources (for example, cities, power plants) that are potentially verifiable or from sectors involving a relatively small number of major emitters (for example, transportation). To mitigate deforestation emissions, the focus is on reduced tropical deforestation and degradation[2].

Land and ocean sinks are usually not included in global mitigation policy frameworks at the moment because they are considered a 'common service'. The goal here is to attribute CO_2 sinks to regions where sink fluxes occur. By the rules of the Kyoto Protocol for instance, only a very small fraction of managed land can be credited as carbon sinks by countries, and this has already ignited controversies[3], whereas the remainder of the land is considered to be a non-human-induced sink[4,5]. Yet, there is causality between sinks and anthropogenic CO_2 emissions. During the Holocene epoch before the industrial era, the atmospheric CO_2 concentration varied by small amounts, showing that in the absence of anthropogenic emissions, land and ocean sinks must be close to zero. It is the human-caused emission of CO_2 from fossil fuel and land-use change that causes the present ocean sink, mainly through increased partial pressure of CO_2 between atmospheric and ocean-dissolved CO_2 (ref. 6). It is also anthropogenic activities that cause terrestrial sinks. Some sinks are directly attributable to actions by individual countries, such as forest management, land-use change and, to some extent, short-range nitrogen deposition. Other sinks are attributable to the entirety of greenhouse gas emissions through the effect of increased CO_2 concentrations and the resulting climate change.

Similarly, it is also anthropogenic activities such as forest management, land-use change, nitrogen deposition, increased CO_2 and climate change that create sinks in terrestrial ecosystems[7].

The role of CO_2 sinks provided by terrestrial ecosystems and the ocean thus deserves more attention for determining the potential for the success of CO_2 mitigation strategies. Terrestrial ecosystems, mainly forests, and the oceans, remove on average each year 54% of CO_2 emitted by deforestation and fossil fuel combustion[1]. Were it not for these sinks, the concentration of atmospheric CO_2 would increase more than twice as fast as observed. Here, we develop two regionalized attribution approaches for natural sinks as services that ameliorate the increase in atmospheric CO_2. We attribute the historical and future increase in atmospheric CO_2 to different regions using two alternative approaches that both include sinks. In one approach, each region is attributed the 'domestic' sink that occurs within its territorial boundaries. In the second approach, each region has a share of a global sink created indirectly through the contribution of that region to the global rise in atmospheric CO_2. This rise enhances vegetation uptake through CO_2 fertilization and climate change, thereby enhancing the global sink both in its territory and other regions. We apply these two approaches to large regions to demonstrate the methodology and to allow relatively accurate attribution with the available data. This methodology

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Table 1 | Attribution of ΔCO_2 to regional fossil fuel and land-use emissions, and terrestrial sinks (column 2 and 3).

Contribution to ΔCO_2 (ppm) in 2006 by: →	Fossil fuel + land-use emissions by this region	Land sink within the territory of this region	Land sink provided to OECD by this region	Land sink provided to REF by this region	Land sink provided to ASO by this region	Land sink provided to ALM by this region
OECD	97	−11	−6	−1	−2	−2
REF	30	−6	−3	−1	−1	−1
ASO	43	−11	−6	−1	−2	−2
ALM	76	−42	−23	−5	−8	−6
All land	246	−70	−38	−8	−13	−11
Ocean	0	−69	−37	−9	−13	−10
Globe	246	−139	−75	−17	−26	−21

Further breakdown of the 'sink service' provided by each absorbing region to others between 1850 and 2006 is given in columns 4 to 7, according to a choice of attribution based on emitters (see main text). The attribution of the cumulative land sinks is expressed in ppm of ΔCO_2. A negative value is equivalent to a reduction of ΔCO_2. The ΔCO_2 reduction 'service' provided by ocean uptake to each region is shown as well. The corresponding ΔCO_2 are given in Fig. 1a. All numbers are rounded to the ppm.

could in principle be applied on the finer scale of individual countries, but more reliable data on land biosphere sources and sinks would need to be developed.

Here we extend the so-called 'Brazilian proposal' approach, which first proposed to assign emission targets to nations on the basis of their historical responsibility for the anthropogenic greenhouse effect (http://www.match-info.net; refs 8–10). Because of the importance of sinks in the global CO_2 budget, analyses considering both emissions and sinks allow a more comprehensive valuing of the contributing drivers and regions to the atmospheric CO_2 imbalance. There is not a best scientific accounting framework for sinks, as accounting choices necessarily follow value judgements on which and how common resources might be shared. For instance, should CO_2 fluxes into and out of unmanaged ecosystems be considered a globally shared resource? Such choices represent values. Values play a role in selecting accounting systems, as already happens in international climate negotiations. However, once a specific accounting system is decided, the ensuing attribution needs to be scientifically based, consistent and with quantification of its uncertainty. It is this factual attribution that is our primary focus.

Here, we show how the attribution of increased atmospheric CO_2 since pre-industrial times differs between the historical period (1850–2006) and the future (2010–2100), when using our distinct attribution approaches for sinks. Ocean sinks are attributed in the same way in both accounting approaches.

Attributing the increase of CO_2 to regions of the globe

A simplified but comprehensive model of the carbon cycle (OSCAR; ref. 11) is used that allows the increase of CO_2 above pre-industrial levels to be attributed to emitting and absorbing regions (see Methods). Fossil fuel and cement emissions are prescribed from the Carbon Dioxide Information Analysis Center database[12]. The model calculates the global ocean uptake and the regional the land-use flux defined as the net CO_2 balance at any time t, of terrestrial ecosystems affected by a land-use transition before t. For undisturbed ecosystems, OSCAR has CO_2 sinks. The terrestrial net primary productivity (NPP) is considered to scale with the logarithm of atmospheric CO_2 content. The magnitude of this CO_2 fertilization effect is calibrated within ecologically plausible limits[13] to reproduce the observed trends in atmospheric CO_2 (see Methods). In undisturbed ecosystems, the CO_2 fertilization sink depends on the rate of increase in NPP and on the residence time of carbon in biomass, litter and soil organic carbon pools. The excess of NPP over heterotrophic respiration is increased or decreased by processes such as temperature change, radiation quality changes and nitrogen deposition. Some studies[14,15] have shown that for high-emission scenarios, climate change reduces land sinks or can even turn sinks into sources in some regions. These carbon–climate feedbacks are not the focus here, but we tested a scenario where NPP and respiration depend on temperature and found no qualitative difference with the results in the absence of feedbacks.

We seek the share of each emitting region in the global excess of atmospheric CO_2 above pre-industrial levels (ΔCO_2). Thus, in the OSCAR carbon cycle model, we decompose ΔCO_2 into a sum of individual positive (sources) or negative (sinks) contributions from each emitting or absorbing region. This is achieved by numerically 'tagging' the modelled CO_2 molecules emitted from each region, as if they were dye tracers. Carbon emitted each year by a given region, be it fossil carbon (here fossil fuel burning and cement emissions) or deforestation carbon, is subsequently spread through the atmosphere–land–ocean carbon system. A fraction of each region's emissions stays in the atmosphere and adds to the increased CO_2 burden. The rest is absorbed either by the ocean or by land in the same, or another, region.

Attribution of the land sink follows two alternative approaches. The first one attributes terrestrial sinks to the region where the sink occurs. This idea of 'domestic sinks' is close to that of 'full carbon accounting' in current international negotiations. The second one estimates for each region the terrestrial sink that its historical emissions have induced over all other regions, including itself. This approach calculates the causal contribution of emitters to the creation of sinks through CO_2 fertilization effects on increased carbon storage (see Methods).

The ocean sink is also important, absorbing about 25% of fossil and land-use emissions at present[16]. There are many ways in which this ocean sink can be attributed. Here, we adopt the approach that the ocean sink removes the share of excess CO_2 caused by each emitting region in direct proportion to the total excess CO_2 at the time of oceanic absorption (see Table 1), a physically based concept in that physical processes at the ocean–atmosphere interface are not discriminated as function of regionally tagged atmospheric CO_2 molecules.

We note, however, that alternate approaches are possible. For example, as the ocean is a shared resource among all people of the world, it could be argued that its CO_2 uptake should be distributed among regions on a per capita basis, or according to the nearest ocean to a particular region. Under this assumption, people in regions of low carbon emission would be attributed a service to high-carbon-emission regions by allowing 'their' share of the ocean to be used to absorb carbon from high-carbon-emission countries. Here, for simplicity, we consider an attribution based on each region's share of excess atmospheric CO_2.

We consider four land regions, plus the ocean. Each region includes several countries that have similar projected economic development pathways, hence similar fossil fuel and land-use CO_2 emissions trajectories. Projected fossil fuel emissions are from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios A2 (SRES A2) scenario[17]. Future land-use-change emissions are calculated by the OSCAR model, given land-cover projections from the IMAGE 2.2 integrated assessment model for the IPCC SRES A2 scenario[18]. The four land regions are those used by the IPCC Fourth Assessment Report (AR4), countries of the Organization for Economic Co-operation and Development (OECD) in North America, western Europe and Pacific developed, countries of Africa and Latin America (ALM), all Asian countries and Oceania (ASO) and the reformed economies of the former Soviet Union including eastern Europe (REF).

Attribution of the historical increase of CO_2

Adopting the first attribution approach of only domestic sinks for each emitter, Fig. 1a shows each region's share of ΔCO_2 between 1850 and the present day (2006), together with the separate attributed contribution of fossil fuel and land-use emissions and of domestic land sinks. The ocean sink, here not attributed, is shown separately on the right. We estimate with OSCAR a value of ΔCO_2 equal to 107 ppm in 2006, close to the observed value of 101 ± 5 ppm. Clearly, most of this historical increase is attributed to OECD countries (+86 ppm) owing to their large cumulated fossil fuel emissions, early century deforestation in North America and their small land sinks. REF countries contribute a small increase of 24 ppm to ΔCO_2 and the ocean contributes a decrease of −69 ppm. The ASO countries contribute +32 ppm to ΔCO_2, about the same as ALM countries (+34 ppm) but for different reasons. The contribution to ΔCO_2 from ASO countries is due to their cumulative fossil fuel emissions. In contrast, ALM countries have small fossil emissions but high cumulative land-use emissions (Fig. 1a). The attribution of ΔCO_2 to ALM countries is, however, attenuated by their high carbon sinks (tropical forest biomes in OSCAR). The domestic carbon sink of ALM countries is found to have offset 56% of their fossil fuel and land-use emissions since 1850.

Using the second approach of attributing land sinks to the emitters that caused them, Fig. 1c shows terrestrial sinks provided by absorbing regions decrease ΔCO_2 (negative bars in Fig. 1c) as a service to emitters (see data in Table 1). With this attribution approach, we estimate that since 1850 the ALM region has provided an uptake of 23 ppm to the ΔCO_2 of OECD, by far the largest 'sink service' from an absorber to an emitter. An additional 9 ppm of ΔCO_2 of OECD is removed by the combined terrestrial sinks of REF and ASO. Not including the ocean in the attribution, the net balance of OECD domestic sink (credits) compared with foreign sinks (debits) is negative at −21 ppm (11 ppm minus 32 ppm). The second region that is more indebted to others for terrestrial carbon sink services is ASO, with other regions providing an uptake of 11 ppm, of which 8 ppm is provided by land sinks in ALM alone. Over the historical period, the region that has provided the largest net sink service to all others is ALM (36 ppm). Regions REF and ASO are close to neutral with respect to the relative importance of their sources and sinks.

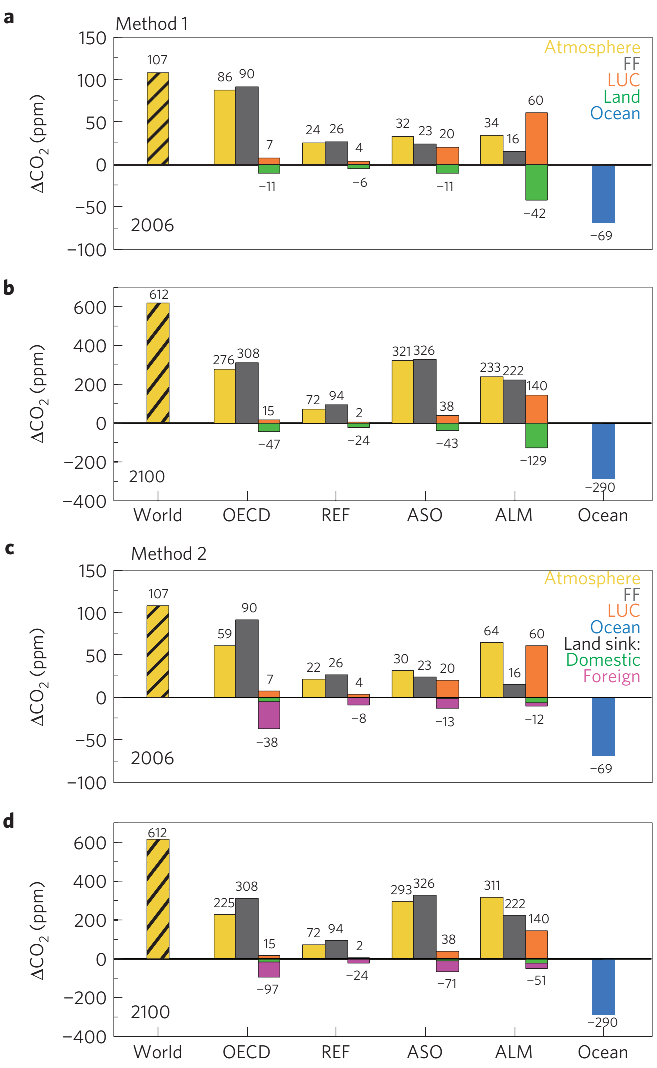

Figure 1 | Attribution of the atmospheric CO_2 increase between 1850 and 2100, assuming that the carbon cycle was in equilibrium in 1850. a, First attribution approach where regional terrestrial 'domestic' sinks are attributed to each absorber region with the OSCAR carbon cycle model. Hatched yellow bar denotes the modelled global ΔCO_2 between 1850 and 2006, resulting from previous emissions and sinks during that period. This modelled global ΔCO_2 is 107 ppm, in line with the observed value of 101 ± 5 ppm. Yellow bars, ΔCO_2 values attributed to each region and their apportionment to emissions and sinks further to the right of each bar; grey, cumulative fossil fuel (FF) emissions; orange, cumulative land-use emissions (LUC); green, terrestrial cumulative sinks, counted negatively because they diminish ΔCO_2; blue, cumulative ocean uptake. **b**, Same but for ΔCO_2 simulated by OSCAR between 1850 and 2100, given the SRES A2 fossil fuel emission scenario and land-use emissions calculated by OSCAR with prescribed land-cover-change forcing in each region (see main text). **c**,**d**, Second attribution approach with regional sinks attributed to each emitter region having caused both a domestic sink, in green, and foreign sinks, in magenta. The ocean sink is shown separately on the right.

Attribution of the future CO_2 increase

Given the SRES A2 fossil fuel emission scenario, the attribution of the projected CO_2 increase in 2100 gives quite a different picture compared with the historical period. Figure 1b shows a modelled value of ΔCO_2 in 2100 of 612 ppm with OSCAR, in the range of three-dimensional (3D) carbon cycle model results (450–740 ppm in ref. 14). ASO countries contribute 321 ppm to ΔCO_2 in 2100, compared with 276 ppm from OECD countries, 233 ppm from ALM countries and 72 ppm from REF countries. The ASO countries are thus projected to have the largest contribution. In the OSCAR model, NPP saturates at high CO_2, therefore the land sink per unit ΔCO_2 weakens in the future, which tends to leave more emissions airborne every year by 2100 under a high-emission scenario such as SRES A2. For all absorbing regions together, the overall sequestration of carbon on land is estimated to provide a decrease in ΔCO_2 of 243 ppm by year 2100 (Fig. 1b) and the overall sequestration in the ocean a further decrease of 290 ppm. This

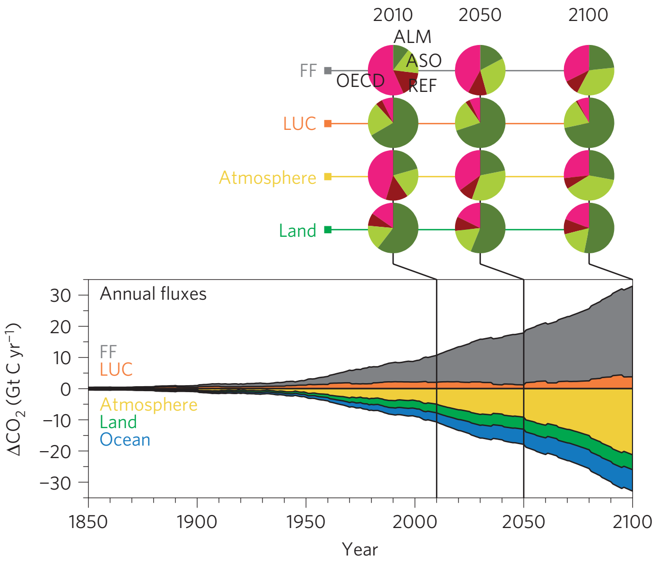

Figure 2 | Changes in global annual CO_2 sources and sinks between 1850 and 2100. Sinks in land and oceans, and the annual increase of CO_2 in the atmosphere, are counted negatively and emissions are counted positively. Annual fluxes are from fossil fuel emissions (grey), land-use change (orange), terrestrial sinks (green), ocean sink (blue) and atmospheric yearly increase (yellow). The four pie charts at the top show the attribution of cumulated emissions, atmospheric increase and domestic sinks occurring in each region for three time slices: 2006, 2050 and 2100.

mitigation of ΔCO_2 is to be compared with the increase of ΔCO_2 caused by emissions alone, in the absence of sinks, of 1,145 ppm.

In Fig. 2, the evolution of the global carbon budget illustrates the fact that the fraction of fossil fuel and land-use emissions remaining airborne increases progressively with time, reaching 64% in 2100 compared with 45% in 2006, owing to the saturation of land sinks in the OSCAR model. For the three time periods of 2006, 2050 and 2100, the pie charts in Fig. 2 give the ΔCO_2 attribution broken down into cumulated fossil fuel emissions, land-use emissions and land sink. For cumulated emissions, a shift of their attribution occurs from OECD towards ASO countries between 2000 and 2100. Such a shift is already discernible in recent fossil fuel annual emission data (Annex B countries having decreased from 64% of global emissions in 1990 down to 44% in 2008; ref. 1). Land-use emissions in the SRES A2 scenario, modelled with OSCAR driven by the IMAGE 2.2 land-cover-change projections[18] and calculating net CO_2 fluxes from land-cover transitions between forest, croplands and grasslands, remain dominated by ALM countries throughout the twenty-first century. These countries alone contribute 66% of cumulated land-use emissions in 2006, but are projected to contribute 72% in 2100 in the scenario studied here. Despite intense land use, ALM countries remain the largest providers of land sink service to emitting regions, including themselves. The share of ALM into the land carbon storage change declines in the future, however, whereas the share of OECD and REF regions increases. This is because in IMAGE 2.2 land-cover-change scenario, deforestation continues in ALM until late in the twenty-first century (resulting in CO_2 emissions in OSCAR), whereas OECD and REF keep stable areas of temperate and boreal forests[18] with long residence times of carbon in soils, enabling carbon storage. This result obviously depends both on the land-cover-change scenario and on the terrestrial carbon cycle model used.

We also tested an attribution of idealized climate feedbacks, by incorporating into OSCAR a linear response of NPP to temperature change and a Q_{10} response of heterotrophic respiration, with the NPP response being calibrated to the results of a 3D Earth system model (see Supplementary Information). An additional ΔCO_2 of 38 ppm is calculated from the feedback. Once attributed, this term does not qualitatively change the results shown in Fig. 1. In case of a large positive feedback occurring in one region, however, the contribution of climate change to the attribution of sinks to emitters will be much more significant. In particular, a threshold-like response to climate change could cause an abrupt drop in sinks, or a large loss of CO_2 from natural reservoirs. In that case, one could attribute to each emitter the ΔCO_2 caused by passing such a threshold, in proportion to the amount of climate change that this emitter has created before the threshold is reached.

We show that it is possible to attribute the increased atmospheric CO_2 burden to emitting regions, accounting for their sink function and for the ocean, treated here as a global ‘sink service’. These first results contribute towards comprehensive, consistent and transparent frameworks for attributing the atmospheric CO_2 excess, which could be further enriched by detailed analysis, for example, using more realistic spatially detailed land and ocean carbon cycle models. Our calculations (using a simplified carbon cycle model and estimates of regional historical land carbon fluxes) are subject to uncertainties. We do not claim that the results obtained here with a simplified model are accurate enough to serve as a quantitative basis for negotiating emission reductions or trading carbon sink services.

There are many other factors that could influence the results, but these are unlikely to alter the sign or order of magnitude of our findings. The nonlinear response of ecosystem carbon fluxes and storage to climate is not accounted for in our approach. If increased decomposition of soil carbon in response to warming or if increased water stress on tropical forests[14,15] were incorporated in our carbon cycle model, the role of land sinks in decreasing ΔCO_2 by 2100 would be lessened. To account for these carbon–climate feedbacks, our simple model could be calibrated to account for the impacts of climate change on land sinks, from the results of more complex Earth system sodels. Similarly, the ocean carbon cycle sensitivity to climate would need to be accounted for in future studies. Here, the only sources of nonlinearity in the carbon cycle are the NPP saturation at high CO_2, the land-use effects on the carbon residence time in ecosystems and a weak nonlinearity in ocean chemistry[19]. Another global adverse impact of human activities that could be attributed to fossil fuel emitters using our method is the acidification of the ocean, counted proportional to CO_2 emitted from each region and absorbed by the oceans. Beyond attribution of ΔCO_2 to emissions, a higher order attribution to emission socioeconomic drivers such as city sprawl, energy production systems, manufacturing industries and trade is possible, which would provide a more direct link between policy action and atmospheric CO_2. Finally, with a major upgrade of carbon observing systems, using *in situ* networks[20] and satellite observations[21], regional carbon sinks could be measured with high enough accuracy that the role of each region in the increase of CO_2 could be better quantified.

Ultimately, any discussion of attribution of ΔCO_2 depends on accurate estimates of emissions from human activities, an appropriate representation of the carbon cycle and decisions about how to treat carbon uptake by the land biosphere and the oceans. Thus, attribution depends on both science and social values. Under any reasonable set of assumptions, the largest share of ΔCO_2 up to the present can be attributed to the developed countries, but the share attributed to the developing world is rapidly increasing. For an intensive emission scenario such as SRES A2, developing countries contribute the largest share of ΔCO_2 by 2100 because their emissions surge in the coming decades and sinks lag behind. In this context, regionalized attribution of land and ocean sinks is critical to provide options for policy, so that absorber regions can benefit from incentives to maintain or enhance the ‘sink service’ they provide to themselves and to others.

Methods

Model description. The OSCAR model[11,22–24] used in this study includes: prescribed emissions from fossil fuel combustion and cement factory based on energy-use statistics since 1850 and economic projections of the SRES IPCC scenarios up until 2100[17]; a calibrated ocean uptake module used for former IPCC assessment reports[19]; a terrestrial ecosystems uptake module calculating the imbalance between NPP and heterotrophic respiration, given residence times in each reservoir[25]; and land-use flux forced by prescribed yearly land-cover-change transitions[26]. The spatial resolution of the model is flexible and the configuration used here is based on four large IPCC economic regions. Within each region, three land-cover types and annual age classes (cohorts of vegetation affected by previous land-use actions) of vegetation are considered. These land-cover-area changes are prescribed from regional census[26] until the present and from the IMAGE 2.2 integrated assessment model scenario for the future[27]. For a specified land-use transition, for example, when a tropical forest is cleared into cropland, the net carbon balance of converted lands is calculated as the sum of losses incurring from 'old' soil carbon decomposition and of 'fresh' gains of carbon by NPP and subsequent litter delivery to the soil from the new vegetation. After such a land-use change, ecosystem carbon pools can remain out of balance for several decades[28]. One important feature is that the residence time of carbon, that is, the carbon mass in a reservoir divided by the flow out of the reservoir, in vegetation is altered in response to changing land use[11]. For example, after the conversion of tropical forests to agriculture, the carbon residence time decreases greatly, which limits future storage of CO_2. The OSCAR-modelled CO_2 growth rate over the period 2000–2006 is 2.0 ppm yr^{-1}, compared with 1.9 ppm yr^{-1} in the observations[1]. The modelled airborne fraction, defined as the ratio of growth rate to the sum of land use and fossil emissions, is 0.45 in OSCAR against 0.46 analysed from actual CO_2 measurements[1]. There is a small bias in favour of the ocean in the proportion of land versus ocean carbon global sinks, but the apportionment of land carbon fluxes between northern and tropical biomes is in broad agreement with atmospheric CO_2 gradients (see Fig. 7.7 in IPCC AR4 (ref. 7), reproduced with OSCAR estimates in Supplementary Fig. S3). The northern hemispheric land sink in OSCAR lies in the lower range of independent atmospheric inversion results[7] and the ocean sink is 2.3 Pg C yr^{-1}, comparable to IPCC AR4, but larger than inversion results, possibly because inversions include natural outgassing of CO_2 by river-delivered carbon to the ocean (0.3 Pg C yr^{-1}) whereas OSCAR simulates the ocean sink of anthropogenic CO_2.

Attribution method. We modified the structure of the OSCAR model (Supplementary Fig. S1) to calculate the fate of CO_2 emissions from each region, which can either end up in the atmosphere or be absorbed by land ecosystems or the ocean. OSCAR is divided into atmospheric, oceanic, plus managed and unmanaged terrestrial reservoirs in each region. The ocean uptake of anthropogenic CO_2 is calculated from an impulse response function model (HILDA model) and accounts for the removal of anthropogenic CO_2 by physical mixing between the ocean surface and deeper waters. For each region we numerically keep track of sinks in unmanaged ecosystems and of land-use-induced sources or sinks for each emitter. Structural nonlinearity in OSCAR implies that $S_{\mathrm{tot}} \neq \Sigma \mathrm{sink}(\Delta C_i)$ where S_{tot} is either the global land sink or the oceanic sink with all emitters, and $S_i = \mathrm{sink}(\Delta C_i)$ is the separate sink induced by the contribution to excess atmospheric CO_2 of the ith emitter alone (ΔC_i). We applied a linearization method to ensure that 100% of S_{tot} is attributed to each emitter, so that $S_{\mathrm{tot}} = \Sigma S'_i$ with $S'_i = \rho_i S_{\mathrm{tot}}$ being the fully attributed sink induced by the ith emitter. The ρ_i coefficients are first equal to $\mathrm{sink}(C_{\mathrm{tot}}) - \mathrm{sink}(C_{\mathrm{tot}} - \Delta C_i)$ and then normalized so as to meet $S_{\mathrm{tot}} = \Sigma S'_i$. This corresponds to the so-called residual normalized attribution method described by ref. 8. We tested other linearization methods discussed by ref. 8 and the resulting ρ_i coefficients were found to be similar to the second digit. Typically, the residual fraction of ΔCO_2 created by the difference $S_{\mathrm{tot}} - \Sigma \mathrm{sink}(C_i)$ due to nonlinearity in both biospheric and oceanic sinks is 10 ppm in 2006 and goes up to 155 ppm in 2100.

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Author contributions

P.C. designed the study and wrote the text. T.G. prepared the model set-up, conducted the simulations and contributed to the text. J.D.P. contributed to the model set-up and to the text, and made the key figures. K.C., M.R.R., J.G.C., A.P., P.F. and S.L.P. contributed to the interpretation of the results and to the text. V.G. developed the original OSCAR model and contributed to the text.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to P.C.

Competing financial interests

The authors declare no competing financial interests.